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Thermal behavior mapping of a phase change material between the heating and cooling enthalpy-temperature curves

Benoit Delcroix[a,*], Michaël Kummert[a], Ahmed Daoud[b]

[a]*Polytechnique Montréal, Department of Mechanical Engineering, 2500 Chemin de Polytechnique, Montréal, QC, H3T 1J4, Canada*
[b]*Laboratoire des Technologies de l'Énergie, Hydro-Québec Research Institute, 600 Avenue de la Montagne, Shawinigan, QC, G9N 7N5, Canada*

Abstract

This paper presents the results of experimental tests performed on a wall section equipped with phase change materials (PCM). The wall is quickly transferred between cold and warm enclosures to observe the PCM behavior when melting or solidification is interrupted. A 1-D model of the wall based on the enthalpy method is used to identify the enthalpy curves that provide the best fit to experimental data. Results show that the PCM experiences a quick transition between different enthalpy curves when the heat flow direction (heating or cooling) is reversed during phase-change. According to our experiments and to the comparison with the 1-D model, the PCM investigated here follows an enthalpy curve that is very close to the heating curve when a cooling process is interrupted during solidification. If a heating process is interrupted during melting, the PCM follows an enthalpy curve that is located between the heating and cooling curves. This information is important to develop models for PCM used in buildings and further work is required to assess the impact of different factors on the transitional behavior.

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Keywords: Phase change material (PCM); Enthalpy-temperature curves; Latent energy storage; Enthalpy method; Interrupted solidification / melting

1. Introduction

Using phase change materials (PCM) to increase the building thermal mass is a possible solution for peak shaving and shifting of heating and cooling loads [1], [2]. Recent efforts focus on developing models [3], [4] which generally rely on enthalpy-temperature curves which define the PCM thermal behavior during heating and cooling processes.

* Corresponding author.
E-mail address: benoit.delcroix@polymtl.ca

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Nomenclature

A	area [m²]
Bi	Biot number [-]
Fo	Fourier number [-]
h	enthalpy [J/g]
i	node [-]
l	left [-]
m	mass [g]
n	number of nodes [-]
r	right [-]
T	temperature [°C]
U	heat transfer coefficient [W/m²-K]
t	time [s]

The PCM behavior during its two-phase state (liquid-solid state) remains uncertain. For example, if a PCM is cooled down after a partial melting, different scenarios are possible, as shown in Fig. 1. A first scenario suggested by Bony and Citherlet [5] is a transition to the cooling curve using a slope equivalent to the solid or liquid specific heat (wT). Chandrasekharan et al. [6] have suggested a second option (noT) which consists in staying on the heating curve.

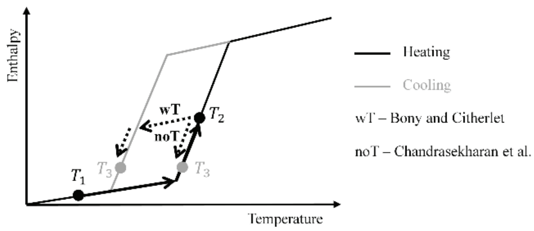

Fig. 1. Possible behavior of a PCM cooled down after partial melting

The objective of this paper is to analyze the behavior of a commercially available PCM after partial melting or solidification. Specific experiments including partial heating and cooling cycles were performed on a PCM-equipped wall and two models were developed for both suggested scenarios. The comparison between experimental and simulated data will be used to identify the behavior of the tested PCM.

2. PCM modeling through an enthalpy method

Classical PCM models are based on the effective heat capacity [7] and enthalpy [8] methods. In this study, a 1-D enthalpy model is used for the PCM, expressed mathematically by the following differential equation:

$$\frac{dh_i}{dt} = \frac{U_{i,l}\,A}{m_i}(T_{i-1} - T_i) + \frac{U_{i,r}\,A}{m_i}(T_{i+1} - T_i) \quad (1)$$

Equation (1) is developed for each node defined in the wall (Fig. 2) and the entire system is then solved using a Forward Time and Central Space (FTCS) finite-difference method [9]. Temperatures are then related to enthalpy through the enthalpy-temperature curves. This method yields stable and reliable results if the Fourier number Fo and the expression Fo (1 + Bi) are lower than or equal to 0.5 [10], respectively for internal and surface nodes.

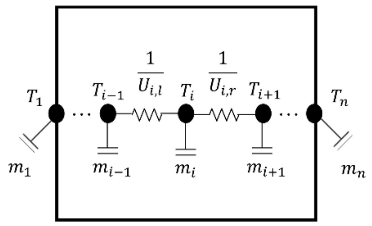

Fig. 2. 1-D finite-difference model of a wall

3. Experimental set-up

The selected PCM is a bio-based product provided in a plastic film with PCM pouches [11]. Additives (gelling agent and fire retardant) are included in the product. Manufacturer data [11] on the PCM includes some properties for the pure PCM and some for the final product with additives. Table 1 summarizes the available data. The density and the thermal conductivity for the PCM with additives have been obtained through additional experimentations.

Table 1. PCM properties

Without additives			With additives		
Phase change temperature	°C	23	Phase change temperature	°C	23
Latent heat storage capacity	J/g	203	Latent heat storage capacity	J/g	165-200
Density	kg/m³	830			
Specific heat (solid)	J/g-K	1.84	Weight per unit surface	kg/m²	1.465
Specific heat (liquid)	J/g-K	1.99	Density	kg/m³	883 *
Thermal conductivity (solid)	W/m-K	0.207	Thermal conductivity (solid and liquid)	W/m-K	0.212 **
Thermal conductivity (liquid)	W/m-K	0.171			

* Experimental measurements (standard deviation: ± 10 kg/m³) – not from manufacturer

** Experimental measurements (standard deviation: ± 0.022 W/m-K) – not from manufacturer

The tested wall consists of a double layer of plastic film with PCM pouches, sandwiched between 2 plywood boards. The wall has an area of 0.6 m² (1 m x 0.6 m) and is instrumented with thermocouples (accuracy: ± 0.5 °C) (Fig. 3). The wall perimeter is insulated to avoid side-effects. The central layer composed of PCM, plastic film and air is modeled as an equivalent 1-D layer (Fig. 4(a)). The main properties of the wall are given in Table 2. Fig. 4(b) presents the enthalpy-temperature curves of the equivalent layer obtained from a model calibration performed on experimental data with complete heating/cooling cycles. Fig. 4(a) also shows the temperature values that are further presented and compared to experimental data. T_{PCM} is compared to the mean value of $T_{in,pcm}$ and T_{in} (Fig. 3) weighted by the mass of each material in the equivalent layer (PCM (76 %) and others (24 %)). T_{si} is compared to the mean value of $T_{si,1}$ and $T_{si,2}$. The same method as T_{si} is applied for T_{so}.

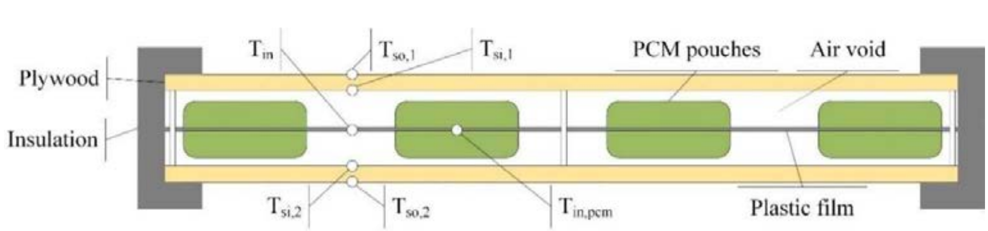

Fig. 3. Instrumented PCM-equipped wall

Table 2. Layers properties

Layer	Thickness [m]	Thermal conductivity [W/m-K]	Density [kg/m³]	Specific heat [J/g-K]
Plywood	0.006	0.084	850	1.25
Equivalent layer	0.017	0.042 (using THERM [12])	223	See Fig. 4(b)

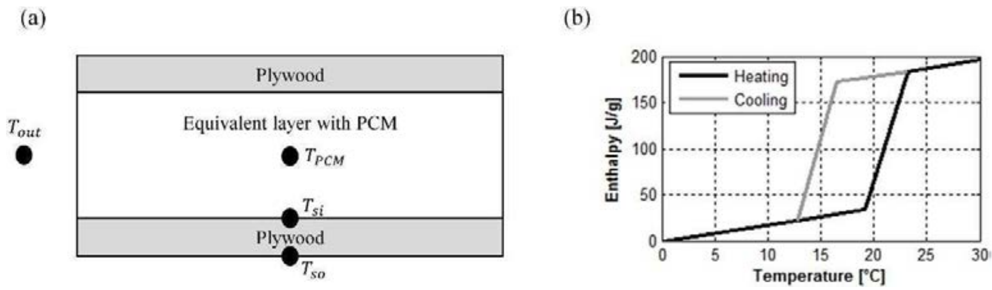

Fig. 4. (a) PCM-equipped wall model; (b) Enthalpy-temperature curves of the equivalent layer

4. Results

4.1. Experimental data

Two series of experiments were performed on one PCM-equipped wall. Fig. 5(a) presents the interrupted heating scenario where the PCM-equipped wall, initially at a uniform cold temperature, is heated up by quickly transferring the wall into a warmer environment, until the PCM starts melting. Before the end of the phase change, the wall is quickly transferred back into the colder environment. The interrupted cooling presented in Fig. 5(b) is the opposite scenario. Temperature results are given for the outside environment (T_{out}), outside surface (T_{so}), the interface between the plywood panel and the central equivalent layer (T_{si}) and the center of the equivalent layer (T_{PCM}). The most important observation is the steep PCM temperature change when heating is replaced by cooling (or conversely) during the phase change. It then reaches a new temperature plateau. This seems to agree with the idea that the PCM switches from the heating curve to the cooling one (or conversely).

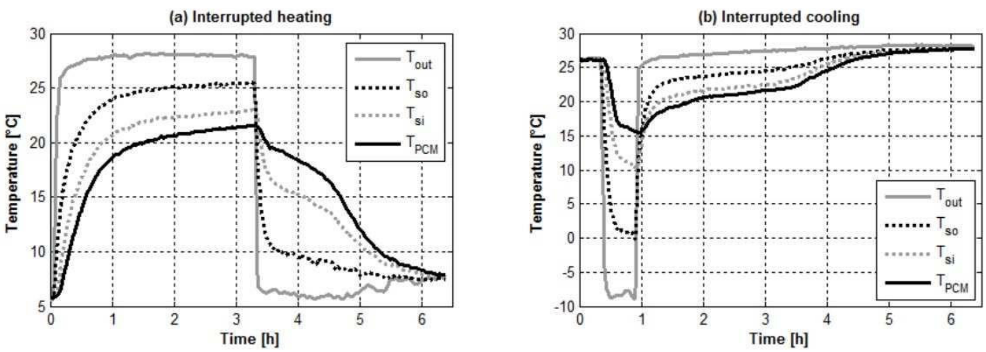

Fig. 5. Experimental data for the interrupted heating (a) and cooling (b) scenarios

4.2. Comparison between experimentations and models

Simulations were performed using two models: first, a model which allows transition between the heating and cooling curves during phase change (Fig. 1 – wT); secondly, a model which considers no transition during phase change (Fig. 1 – noT). Both simulated scenarios are compared to experimental data in Fig. 6. The model without transition does not agree with the experimental data. The model with transition is in good agreement with the experimental data of the interrupted cooling scenario with a root mean square deviation (RMSD) value of 0.37 °C (lower than the measurement accuracy of ± 0.5 °C). The agreement is not as good for the interrupted heating scenario: the "plateau" in the temperature curve associated with solidification starts earlier and is less pronounced in the experimental data than for the model with transition. The experimental results are enclosed between the two modeling options, with and without transition.

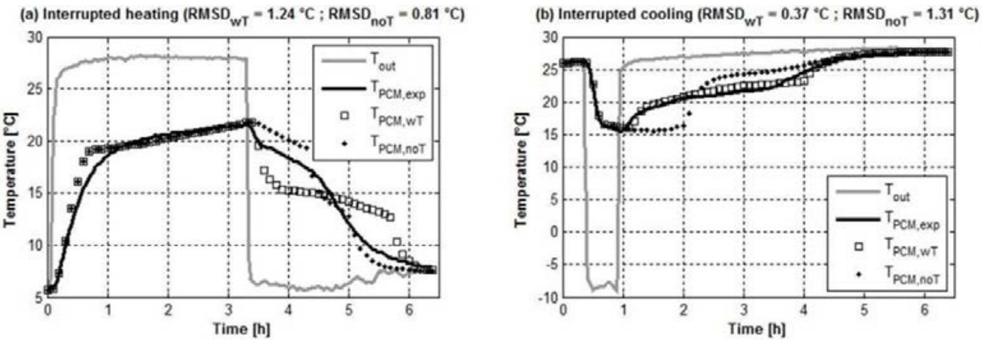

Fig. 6. Comparison between experimental and simulated data for the interrupted heating (a) and cooling (b) scenarios

4.3. Mapping of a solution

An optimization algorithm was used in order to find the enthalpy-temperature curves that match the experimental and simulated data for both tests. The resulting temperature profiles are presented in Fig. 7; they show a good agreement with experimental data, with RMSD values of 0.64 °C and 0.28 °C, respectively for the interrupted heating and cooling scenarios. Both values are close to the measurement accuracy of ± 0.5 °C.

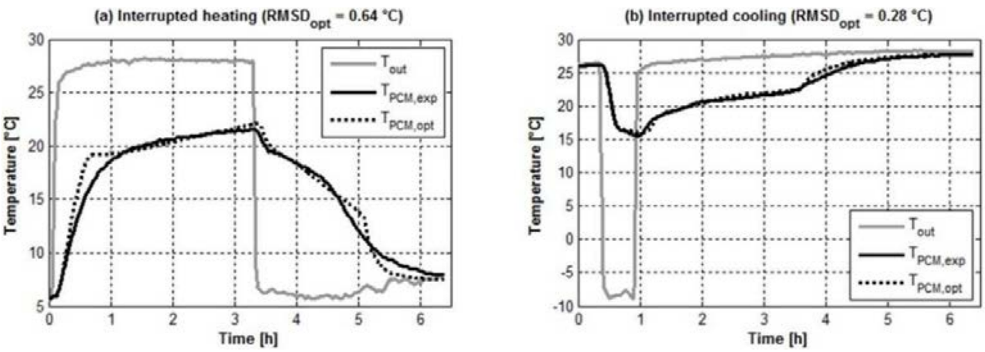

Fig. 7. Comparison between experimental and optimized simulated data for the interrupted heating (a) and cooling (b) scenarios

Fig. 8 shows the path followed by the PCM on the enthalpy-temperature curves for both scenarios according to the optimization results. Initial curves (solid lines) from Fig. 4(b) are preserved while the optimized curve (dotted lines) followed by the PCM after the transition is also presented for each test. The PCM is first heated/cooled from T_1 to T_2, following the initial heating/cooling curve. A partial transition then occurs between T_2 and T_3 towards an intermediate cooling or heating curve. The assumption that the transition follows a line of constant specific heat close to the solid and liquid values is verified in our case. The PCM then follows this intermediate curve until the end of the phase change (between T_3 and T_4), and it finally returns to the initial enthalpy curve between T_4 and T_5.

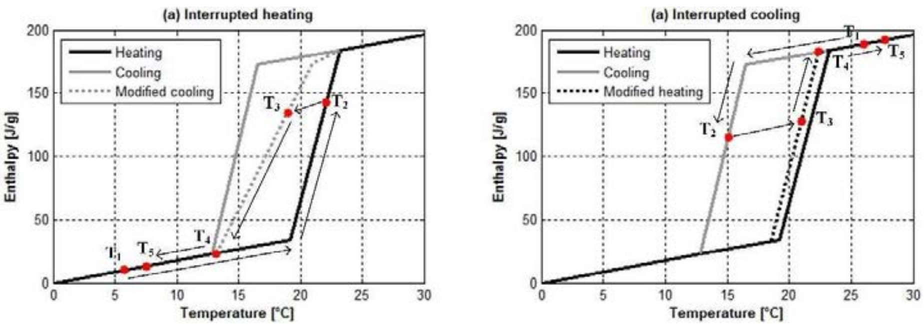

Fig. 8. Thermal behavior mapping of the optimized solution

The location of the intermediate curve (Fig. 8) between the heating and cooling curves is different in the interrupted heating and cooling scenarios. Experimental data (Fig. 5) shows that the driving force to heat up or cool down the wall is different in both cases: the difference between the environment and PCM temperatures when the transition is initiated is about 15 °C in the interrupted heating scenario and 10 °C in the other scenario. This could play a role in the different transitional behavior.

5. Conclusions and further research

This paper presents a comparison between experimental and simulated data in order to evaluate the thermal behavior of a PCM when its phase change is interrupted. Experimentations were performed by quickly transferring a PCM-equipped wall section from a cold to a hot environment, and conversely. In parallel, two models were developed to simulate the thermal behavior of a PCM-equipped wall according to two scenarios to describe the behavior of the PCM after an interrupted melting or solidification process. The comparison between experimental and simulated data shows that the PCM studied in this paper is subject to a rapid transition between the heating and cooling curves if the heating or cooling process is interrupted during phase change. For the interrupted heating process, the transition is partial and the PCM follows an enthalpy curve which is located between the heating and cooling curves. Further research will aim at assessing the impact of different factors such as the heat transfer rate on the transitional behavior.

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